

Quantum Holography, Quantum Ellipsometry, and Beyond...

(Quantum Imaging and Quantum Metrology with Entangled-Photon States)

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Bahaa Saleh, and Malvin Teich**



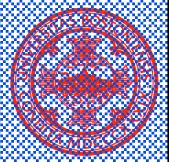
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QUANTUM IMAGING LABORATORY

at Boston University

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NSF (CCR, CISE, AMOP)
Packard
DARPA Quist
NRO
CIPA
NIH
MIT LL
BUPC

Quantum Imaging Program at Boston University

Brief history:

1982 - Klyshko (theory)

1985 - 1990 Malygin, Penin, Sergienko (experiment)

1992 - 1996 Pittman, Strekalov, Klyshko, Sergienko, Rubin, Shih (experiment)

1993 - Quantum imaging with squeezed states

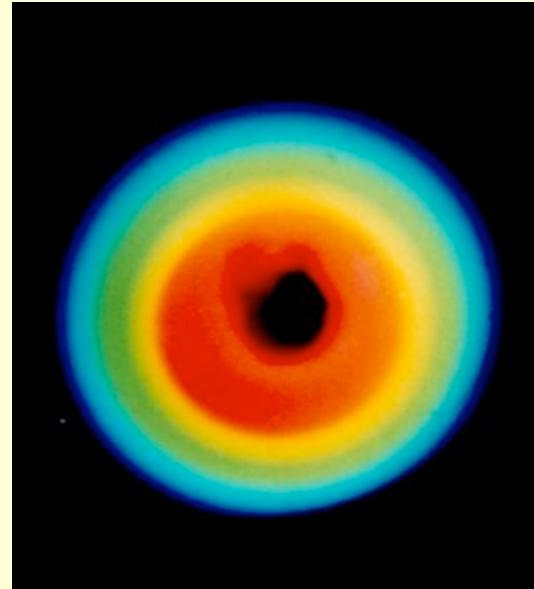
Kumar, Lugiato, Gatti, Kolobov, Fabre, ... (QUANTIM)

1996 - 2002 Quantum Imaging Laboratory at BU

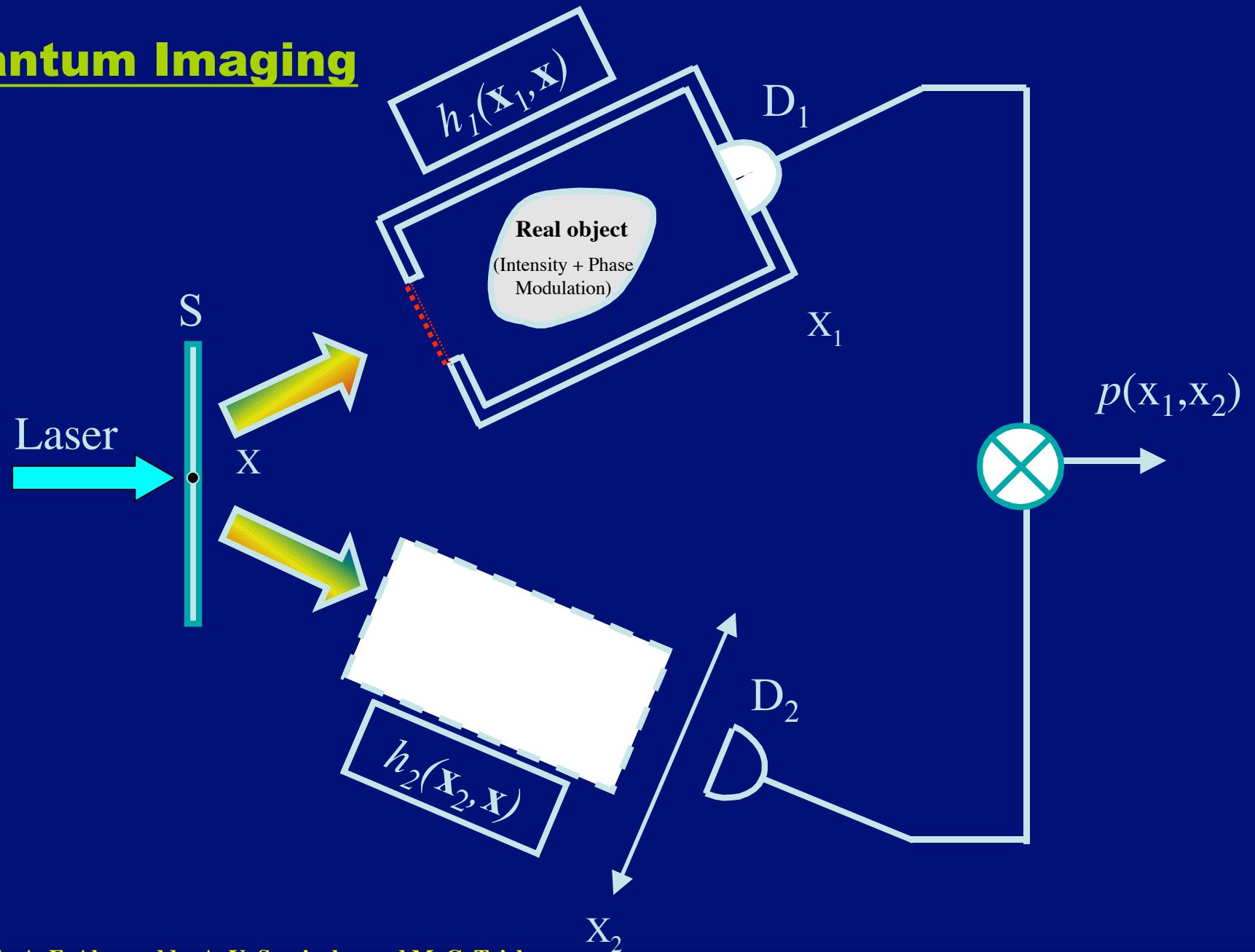
Sergienko, Saleh, Teich (theory + experiment)

Parametric Down Conversion - source of entangled states

Phase Matching TYPE I



Quantum Imaging



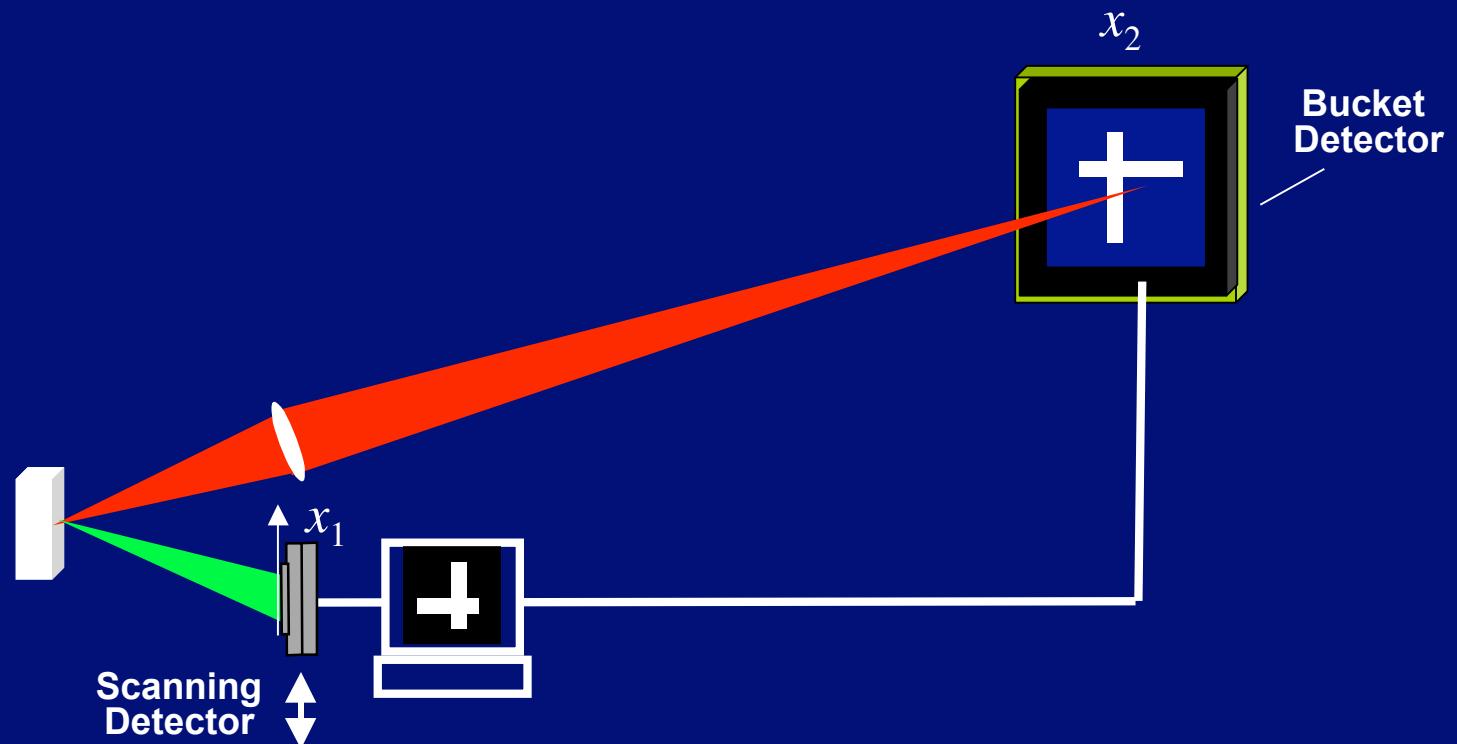
B. E. A. Saleh, A. F. Abouraddy, A. V. Sergienko, and M. C. Teich

"Duality between partial coherence and partial entanglement", *Physical Review A*, 043816 (2000).

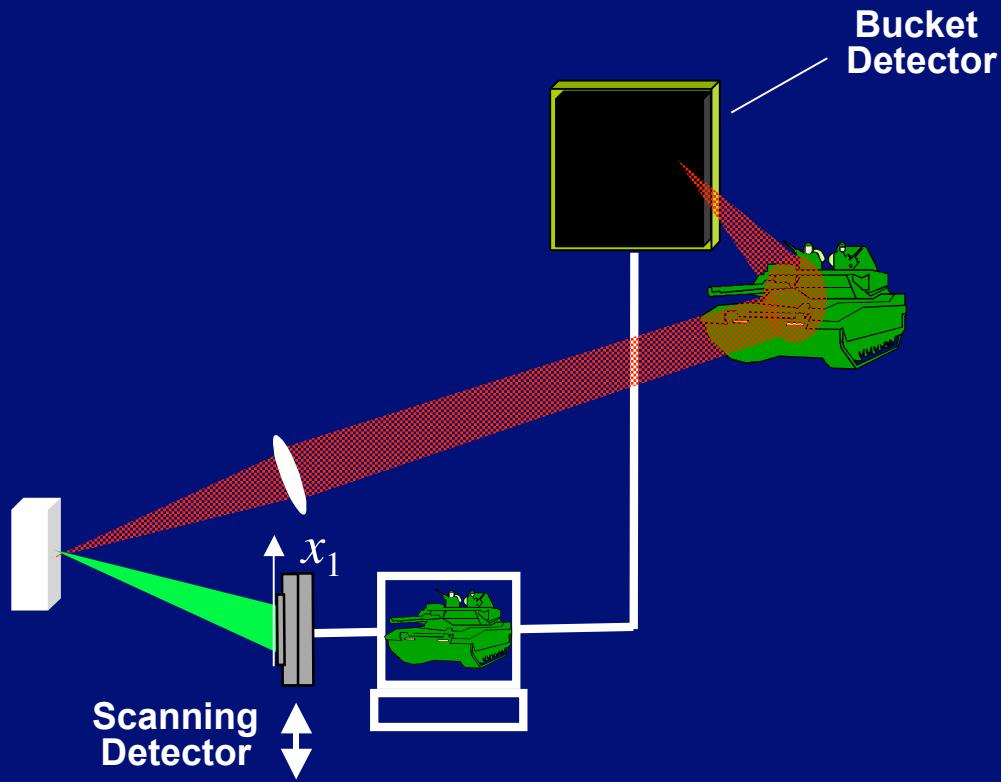
T. B. Pittman, D. V. Strekalov, D. N. Klyshko, M. H. Rubin, A. V. Sergienko, and Y. H. Shih
"Two-Photon Geometric Optics", *Physical Review A*, v.53, p.2804 (1996).

T. B. Pittman, Y. H. Shih, D. V. Strekalov, and A. V. Sergienko
"Geometrical Imaging by Means of Two-Photon Quantum Entanglement" *Physical Review A*, v.52, p.R3429 (1995).

- Bucket detector
- Transmissive object adjacent to detector (intensity modulation)



- Partially Reflective object
- Both intensity and phase modulation

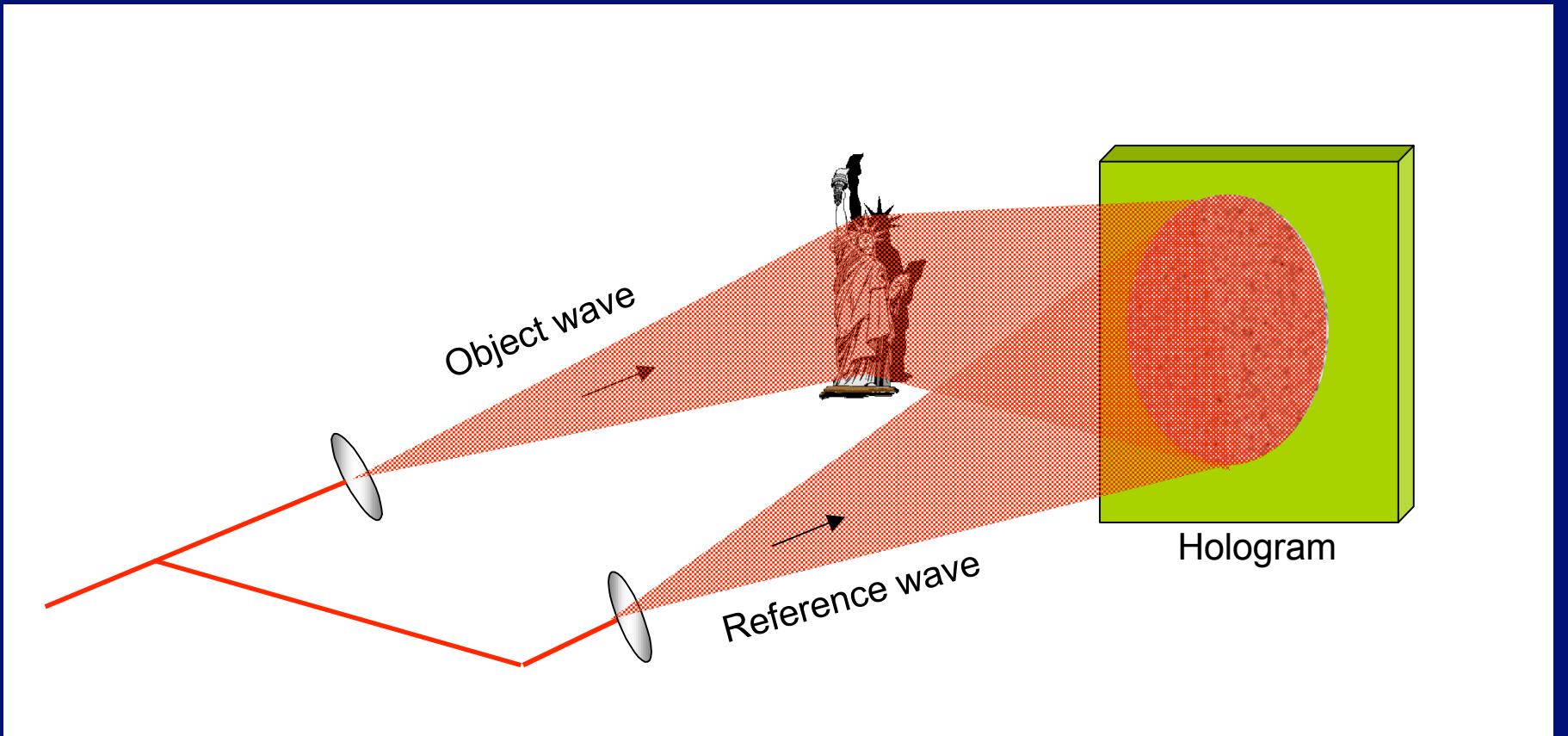


A. Abouraddy, B. E. A. Saleh, A. V. Sergienko, and M. C. Teich
 “Entangled Photon Fourier Optics”, *J. Opt. Soc. Am. B*, v. 19, 1174-1184 (2002);

A. Abouraddy, B. E. A. Saleh, A. V. Sergienko, and M. C. Teich
 “Role of entanglement in two-photon imaging” *Physical Review Letters*, 87, 123602 (2001).

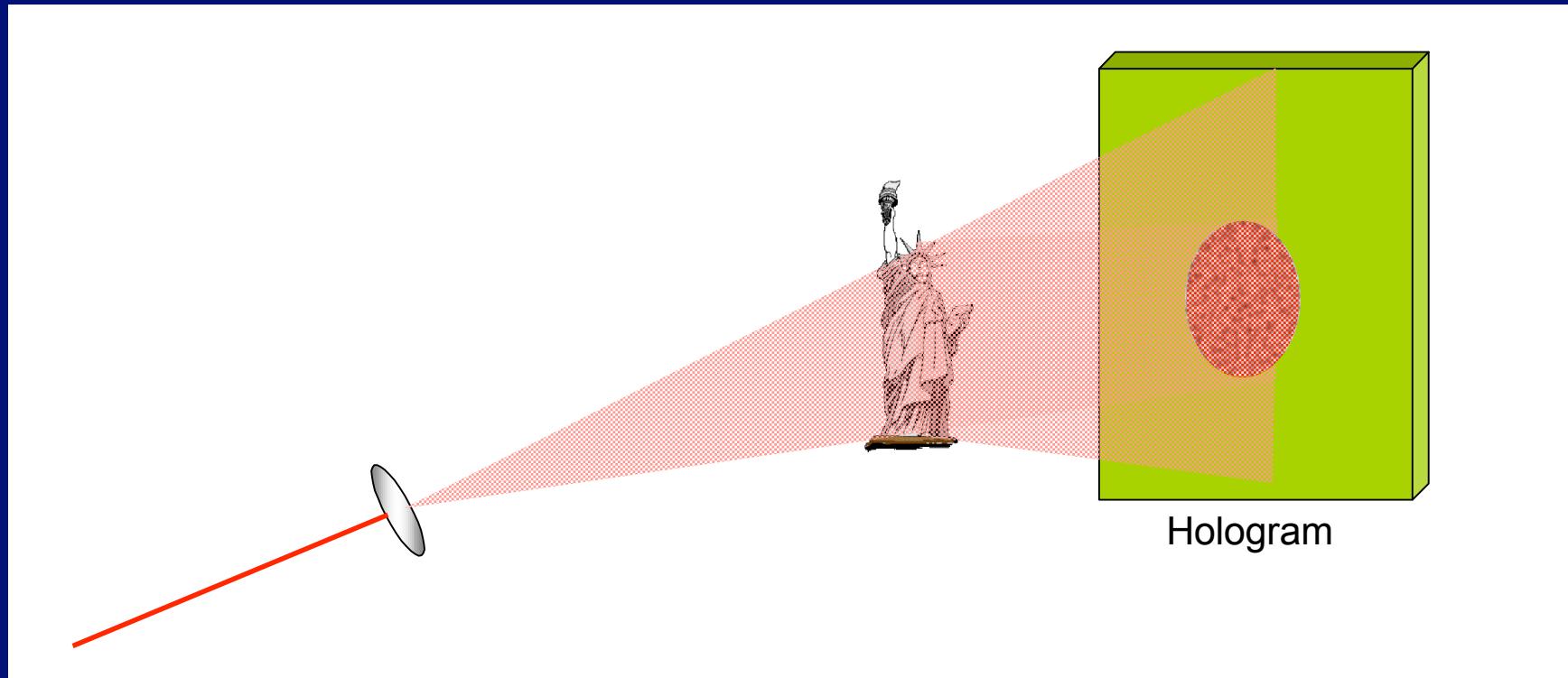
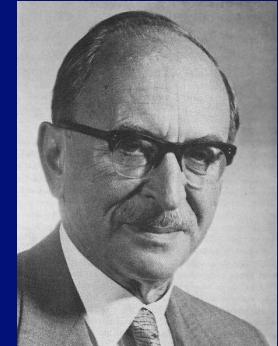
Holography?

= Recording & reconstruction of
a wave scattered from an object:



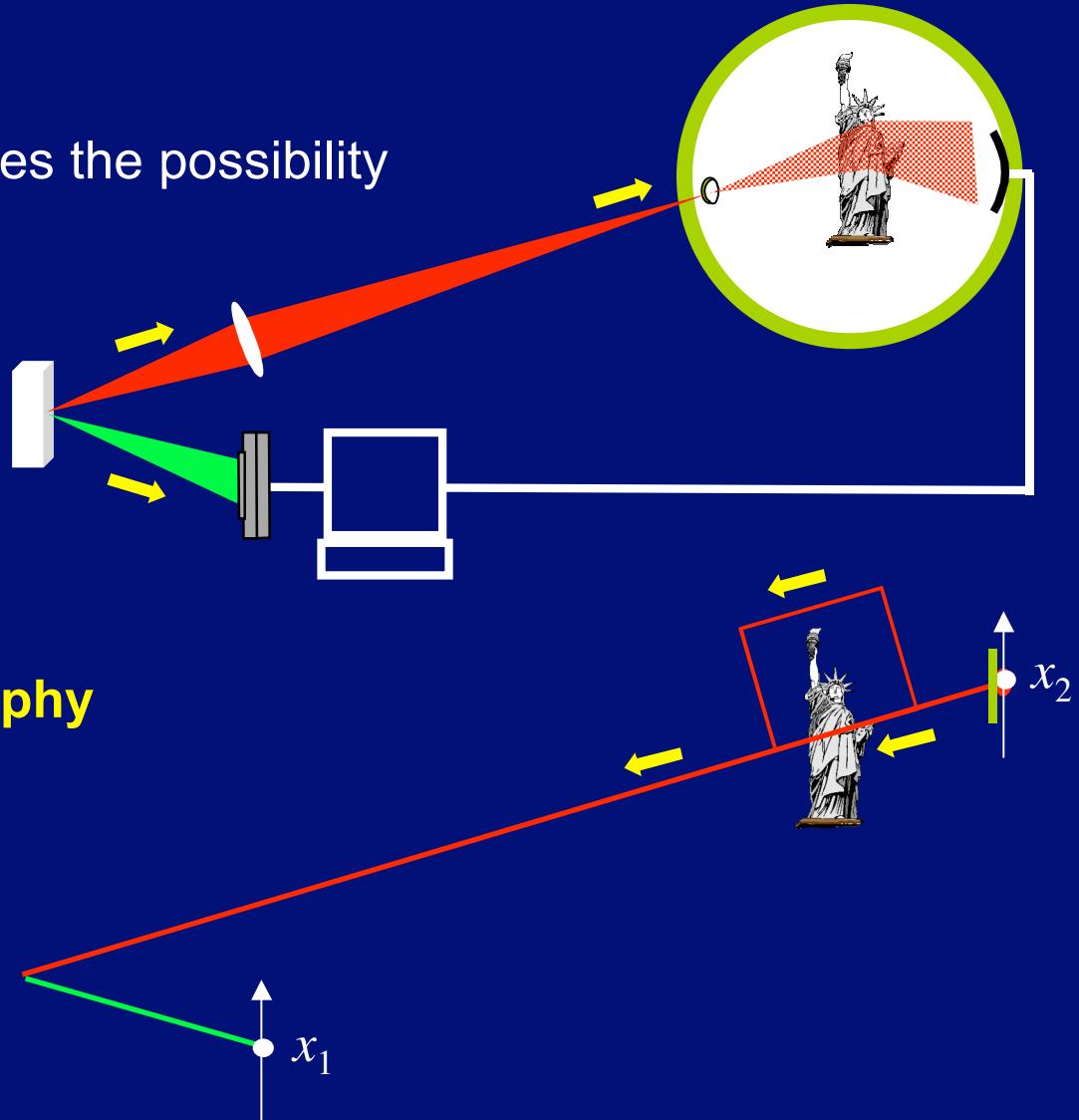
Gabor Holography?

= Self-referenced holography



Entangled 2-Photon Quantum Holography

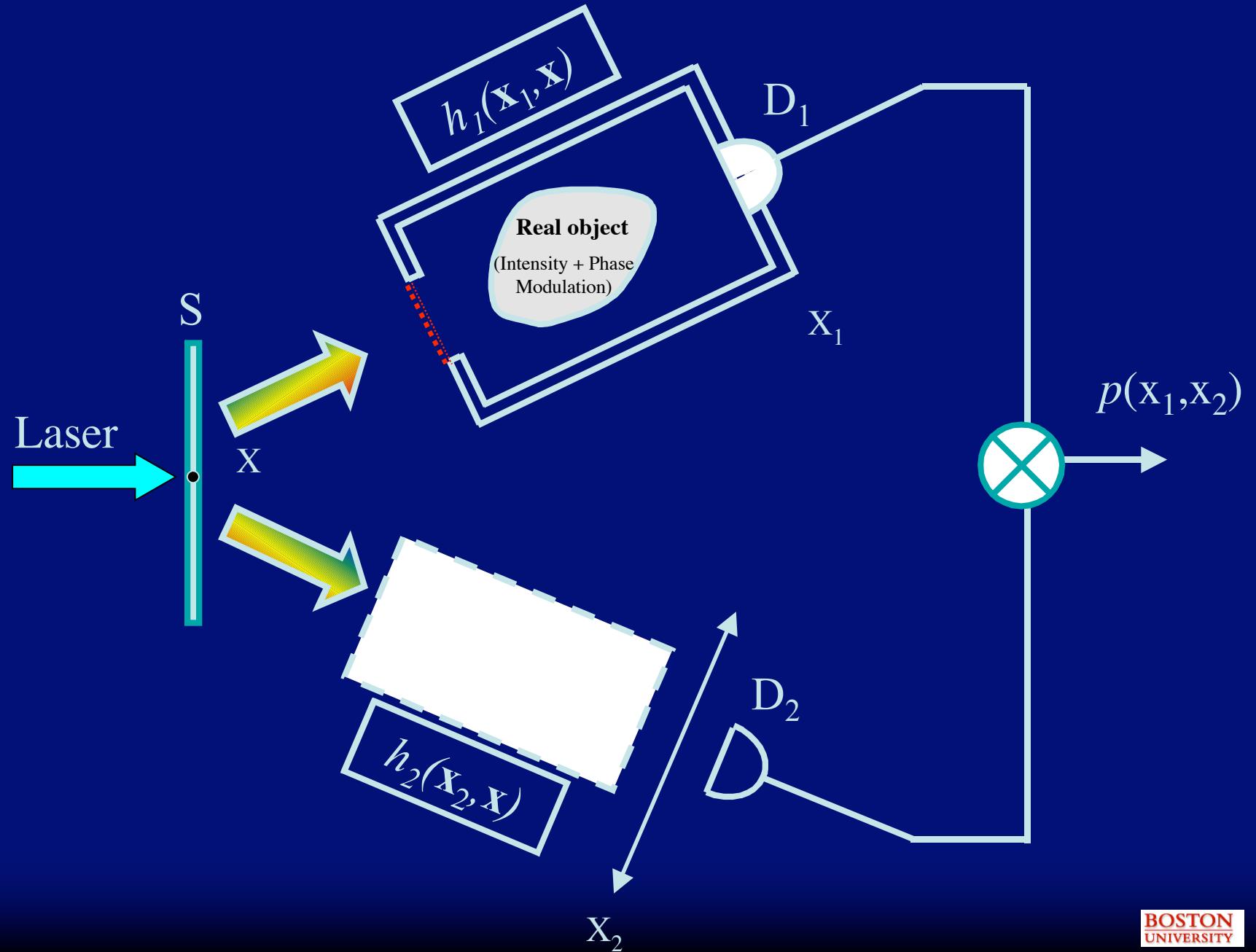
Coherent imaging implies the possibility of holography



Gabor Quantum Holography

A. Abouraddy, B. E. A. Saleh, A. V. Sergienko, and M. C. Teich
“Quantum Holography”, *Optics Express*, v.9, pp.498-505 (2001).

Quantum Imaging/Holography



Quantum Metrology Program at Boston University

Brief historical introduction:

- 1970 - Burnham, Weinberg (experiment)**
- 1977 - Klyshko (theory)**
- 1977- Khitaeva, Penin, Fadeev, Yanait (experiment)**
- 1981 - 1986 Malygin, Penin, Sergienko (experiment)**
- 1987 - Rarity, Tapster (experiment)**
- 1993 - Kwiat, Steinberg, Chiao (experiment)**
- 1992 - 1996 Migdall, Sergienko (experiment)**
- 1996 - 2002 Quantum Imaging Laboratory at BU -
Quantum optical measurement for research and engineering**
- Sergienko, Saleh, Teich (theory + experiment)**

QUANTUM METROLOGY

(Precise Optical Measurements Without Standards)

Absolute calibration of the sensitivity of photodetectors using a biphotonic field

A. A. Malygin, A. N. Penin, and A. V. Sergienko
M. V. Lomonosov Moscow State University

(Submitted 16 February 1981)

Pis'ma Zh. Eskp. Teor. Fiz. 33, No. 10, 493–496 (20 May 1981)

The combined influence of a monochromatic flux of pumping photons and quantum noise on a medium that is not centrally symmetrical results in the appearance of rigorously time-correlated pairs of photons in the spontaneous parametric scattering (SPS) process. The presence of a field of such photon pairs (biphotons) makes it possible to develop a fundamentally new method of determining the absolute quantum efficiency of photodetectors.^{1–3}

PACS numbers: 85.60.Gz, 42.65.Cq

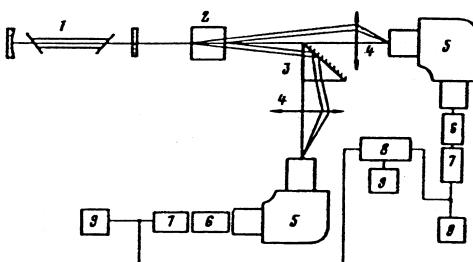


FIG. 1. Block diagram of experimental apparatus for absolute calibration of photodetectors: 1—He-Cd laser; 2—crystal; 3—reflecting rotating prism; 4—lenses; 5—ISP-S1 spectrographs; 6—photo-multipliers; 7—high-speed amplifiers; 8—coincidence circuit; 9—counters.

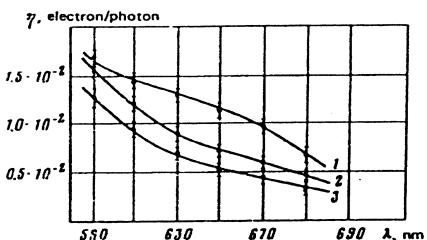
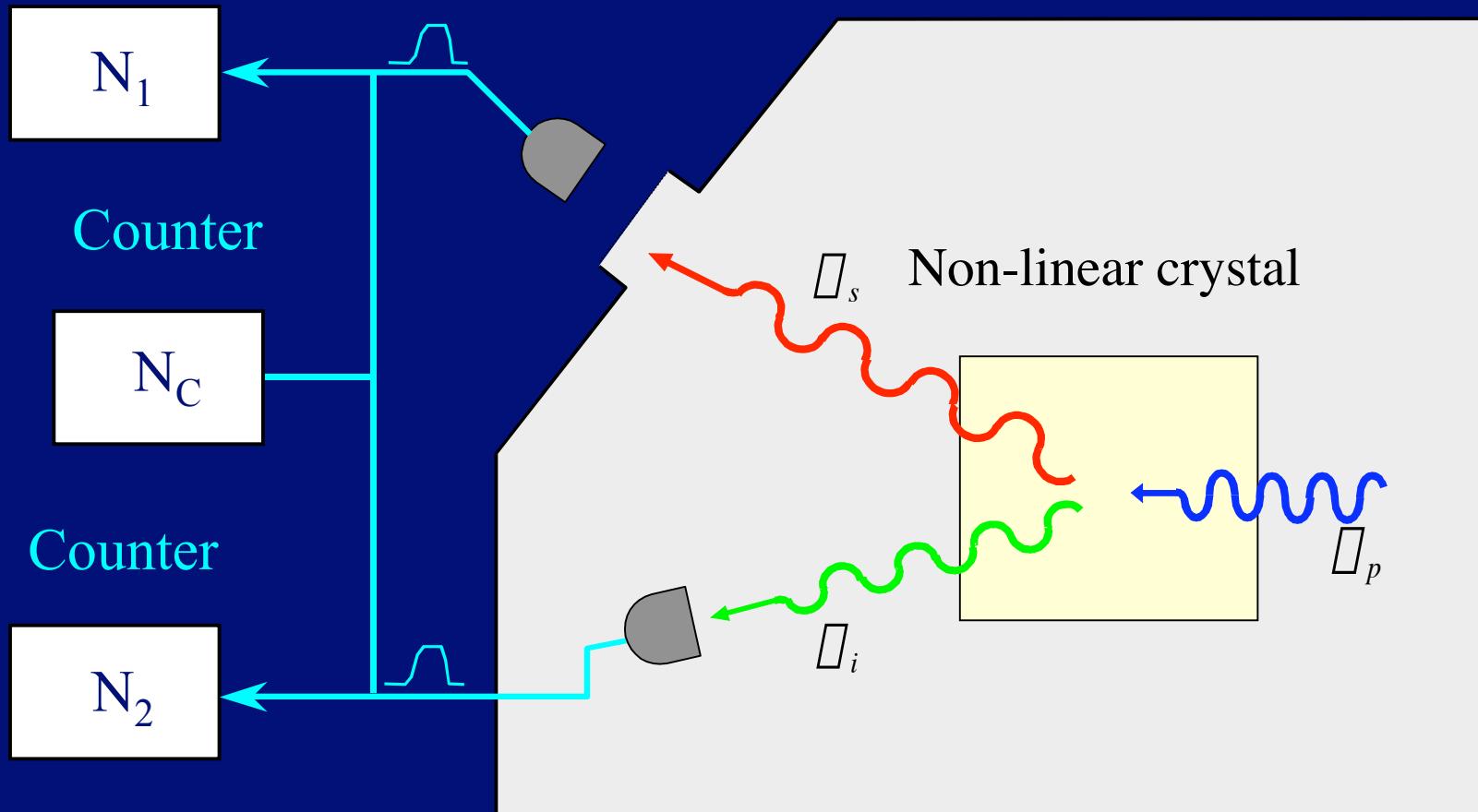


FIG. 3. Experimentally obtained spectral dependences of the quantum efficiency of three FUE-79 systems, 1—PMT integral sensitivity is $S_{\Sigma} = 306 \mu\text{A/lm}$; 2— $S_{\Sigma} = 210 \mu\text{A/lm}$; 3— $S_{\Sigma} = 143 \mu\text{A/lm}$.

Absolute Measurement of Quantum Efficiency without Standards

Counter

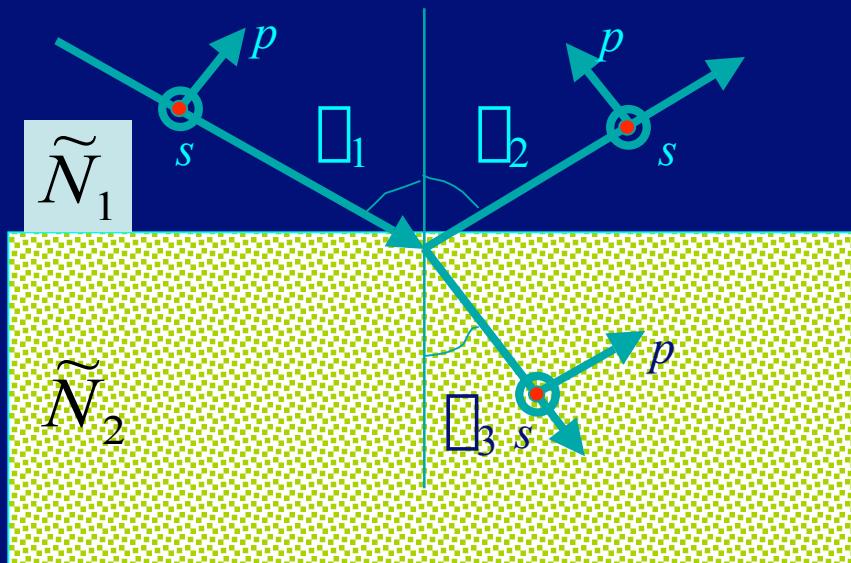


Quantum Metrology for better metrology

Ellipsometry

Characterization of surfaces and thin films

$$\tilde{r}_{12}^p = \frac{\tilde{N}_2 \cos \theta_1 \tilde{N}_1 \cos \theta_2}{\tilde{N}_2 \cos \theta_1 + \tilde{N}_1 \cos \theta_2} = r_{12}^p e^{j\phi_1}$$
$$\tilde{r}_{12}^s = \frac{\tilde{N}_1 \cos \theta_1 \tilde{N}_2 \cos \theta_2}{\tilde{N}_1 \cos \theta_1 + \tilde{N}_2 \cos \theta_2} = r_{12}^s e^{j\phi_2}$$



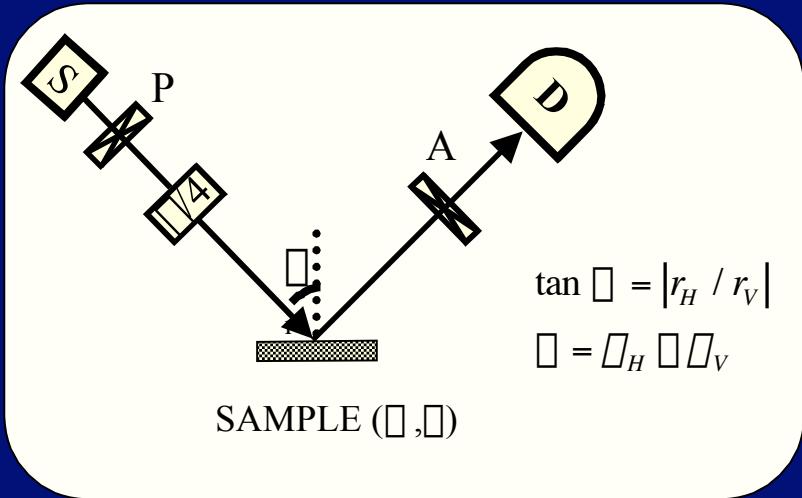
Ellipsometry Equations:

$$\tan \psi = |r_H / r_V|$$
$$\psi = \phi_H - \phi_V$$

Quantum Ellipsometry

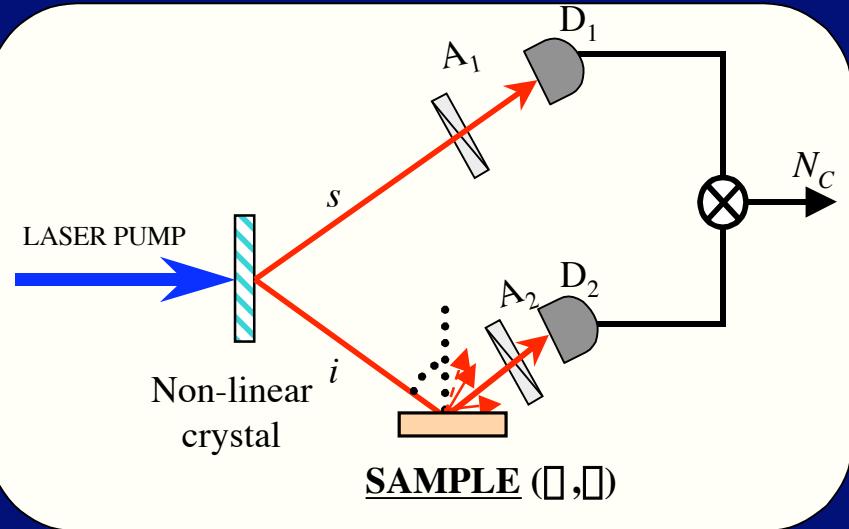
Quantum Metrology for better research and engineering

Conventional Null Ellipsometer



Need calibrated detector efficiency
Need a reference sample
(limited to a single incidence angle and single wavelength)

Entangled-Photon Quantum Ellipsometry



Complete self-reference due to quantum correlation and polarization entanglement between two photons (broadband and available for any angle of incidence)

- Coincidence scheme for optical detection of time-correlated photons alleviate the need for detector calibration.
- Non-local polarization entanglement between photons in the pair provides a universal self-referencing for polarization-dependent measurement because one of twins travels in the air.
- First tests yielded reliable results for different semiconductor materials (Si, GaAs).

- A. Abouraddy, K. Toussaint, A. V. Sergienko, B. E. A. Saleh, and M. C. Teich "Entangled-Photon Ellipsometry", *J. Opt. Soc. Am. B*, v. 19, 656-662 (2002).
• Abouraddy, K. Toussaint, A. V. Sergienko, B. E. A. Saleh, and M. C. Teich "Ellipsometric Measurements Using Photon Pairs Generated by Spontaneous Parametric Down Conversion", *Optics Letters*, v.26, 1717-1719 (2001).

Quantum Ellipsometry Equations

$$N_c = C[\tan \square \cos^2 \square_1 \sin^2 \square_2 + \sin^2 \square \cos^2 \square_2 \\ + 2\sqrt{\tan \square} \cos \square \cos \square_1 \cos \square_2 \sin \square \sin \square_2]$$

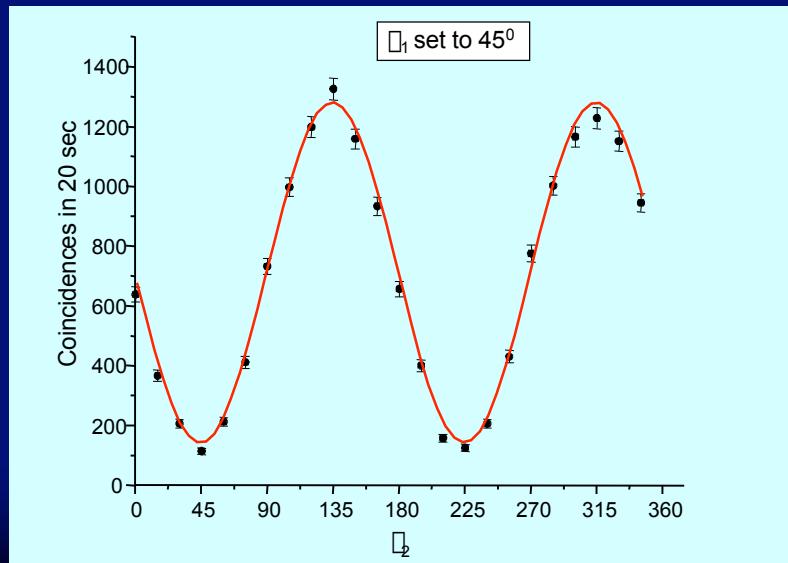
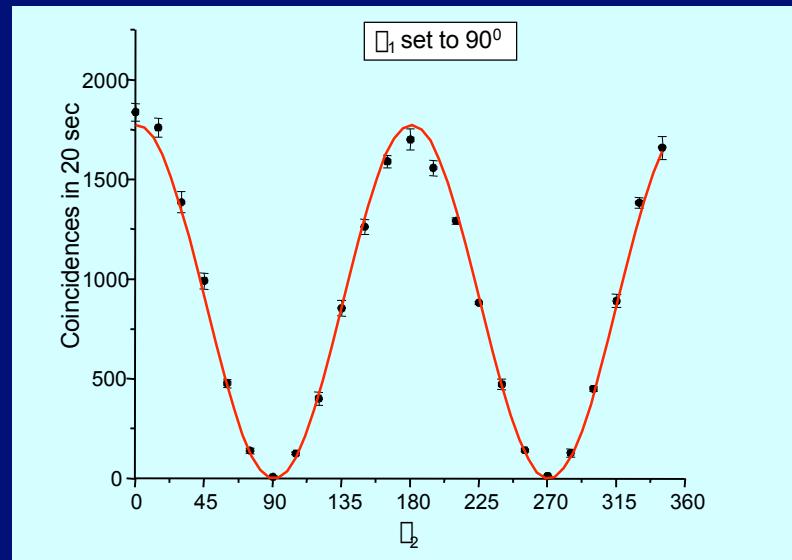
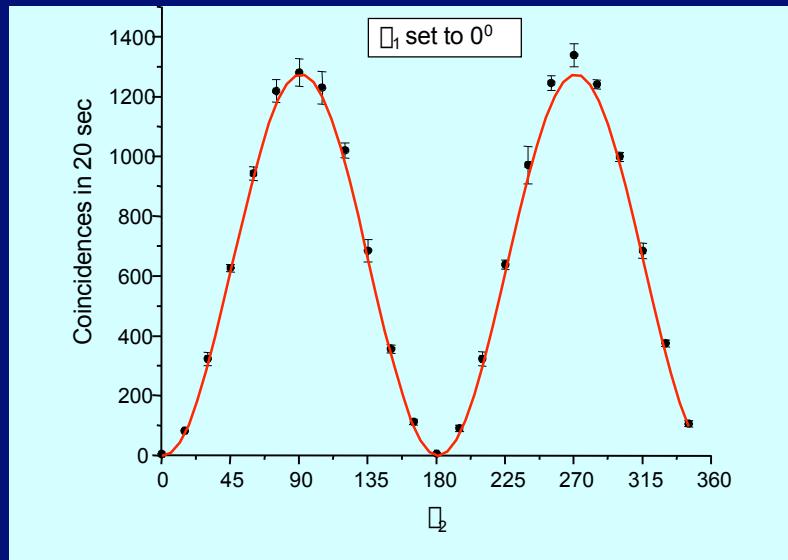
To determine C, set $\square_1 = 90^\circ$: $N_{c_{90}} = C \cos^2 \square_2$

To determine \square , set $\square_1 = 0^\circ$: $N_{c_0} = C \tan \square \sin^2 \square_2$

To determine \square , set $\square_1 = 45^\circ$:

$$N_{c_{45}} = \frac{1}{2} \left[N_{c_{90}} + N_{c_0} + \frac{C}{2} \sqrt{\tan \square} \cos \square \sin(2 \square_2) \right]$$

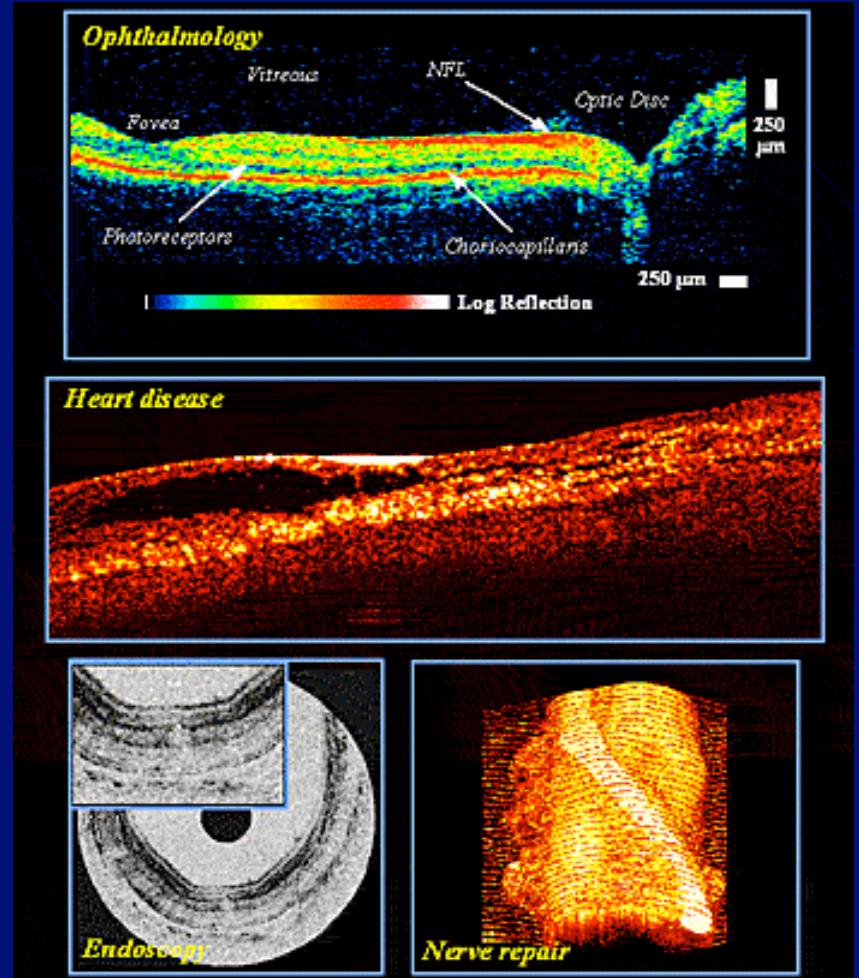
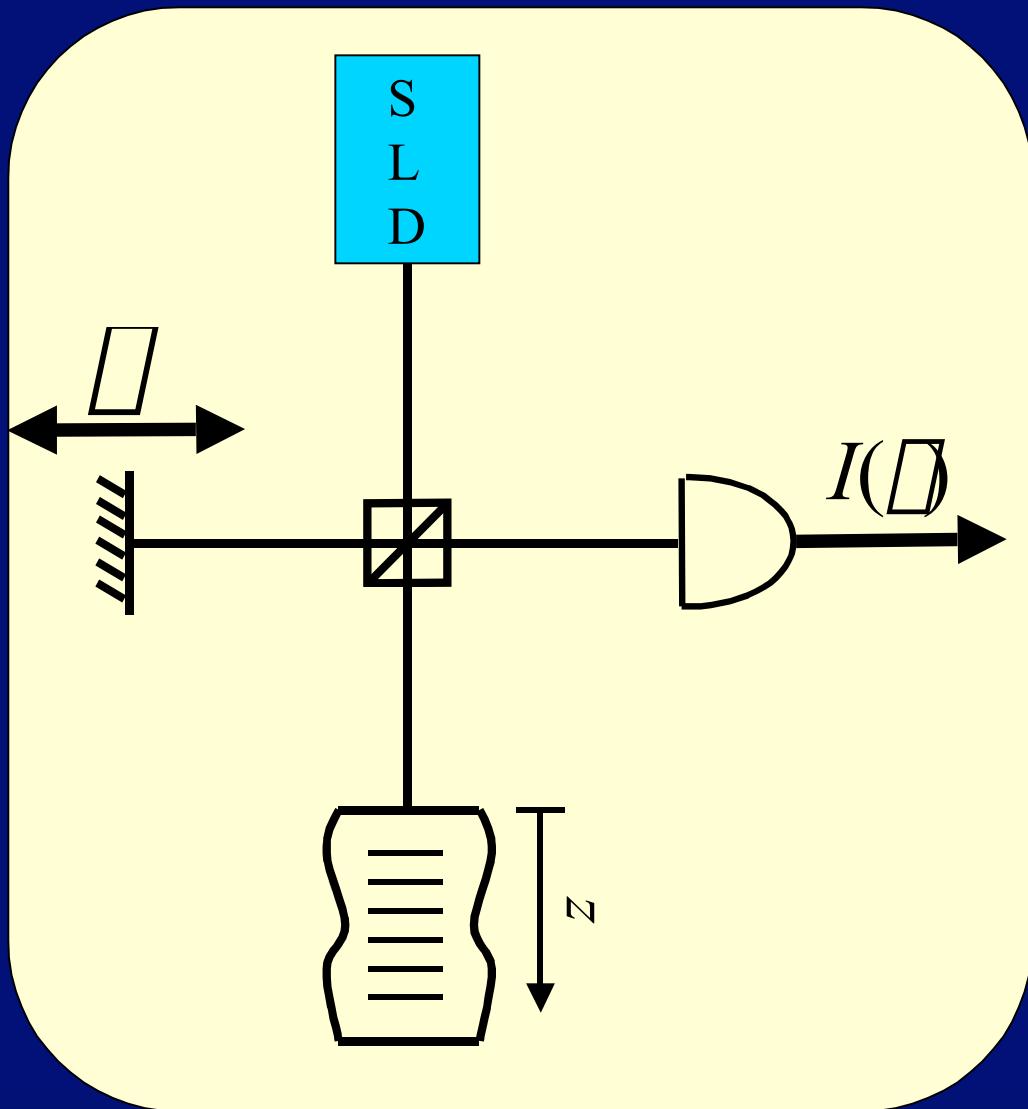
GaAs ($\square = 30^\circ$)



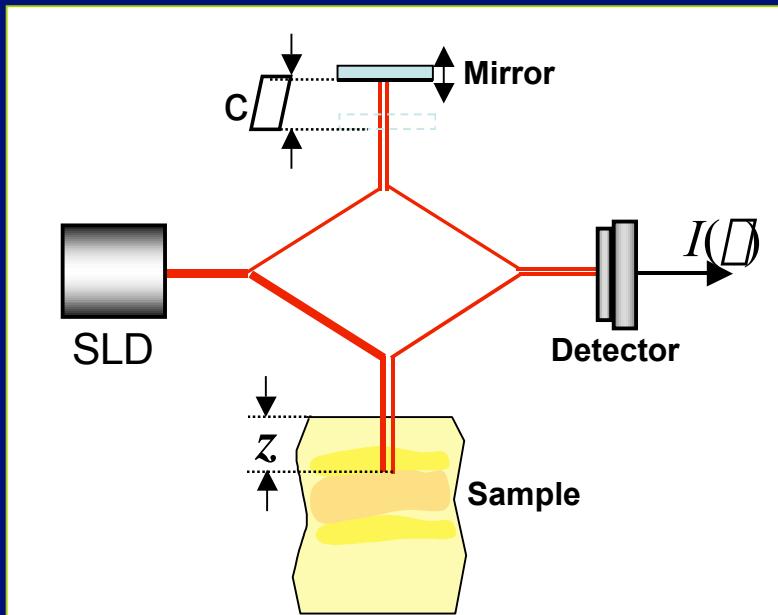
GaAs sample. Angle of incidence is 30° .
Data uses standard deviation for error.

Expected \square and \square are 40.4° and 180° ,
respectively. We obtained 40.5° and 179.8° .

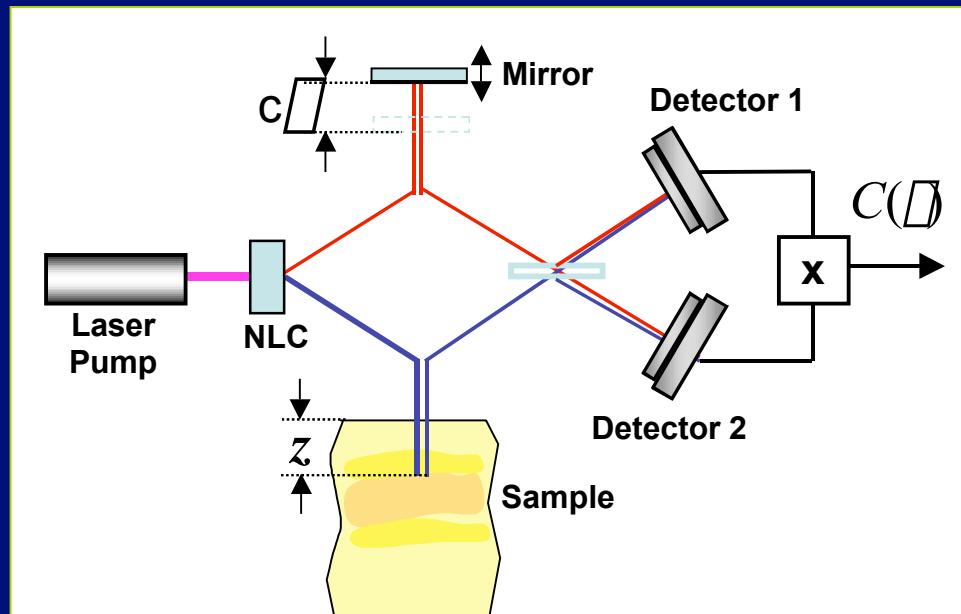
OPTICAL COHERENCE TOMOGRAPHY (OCT)



OCT



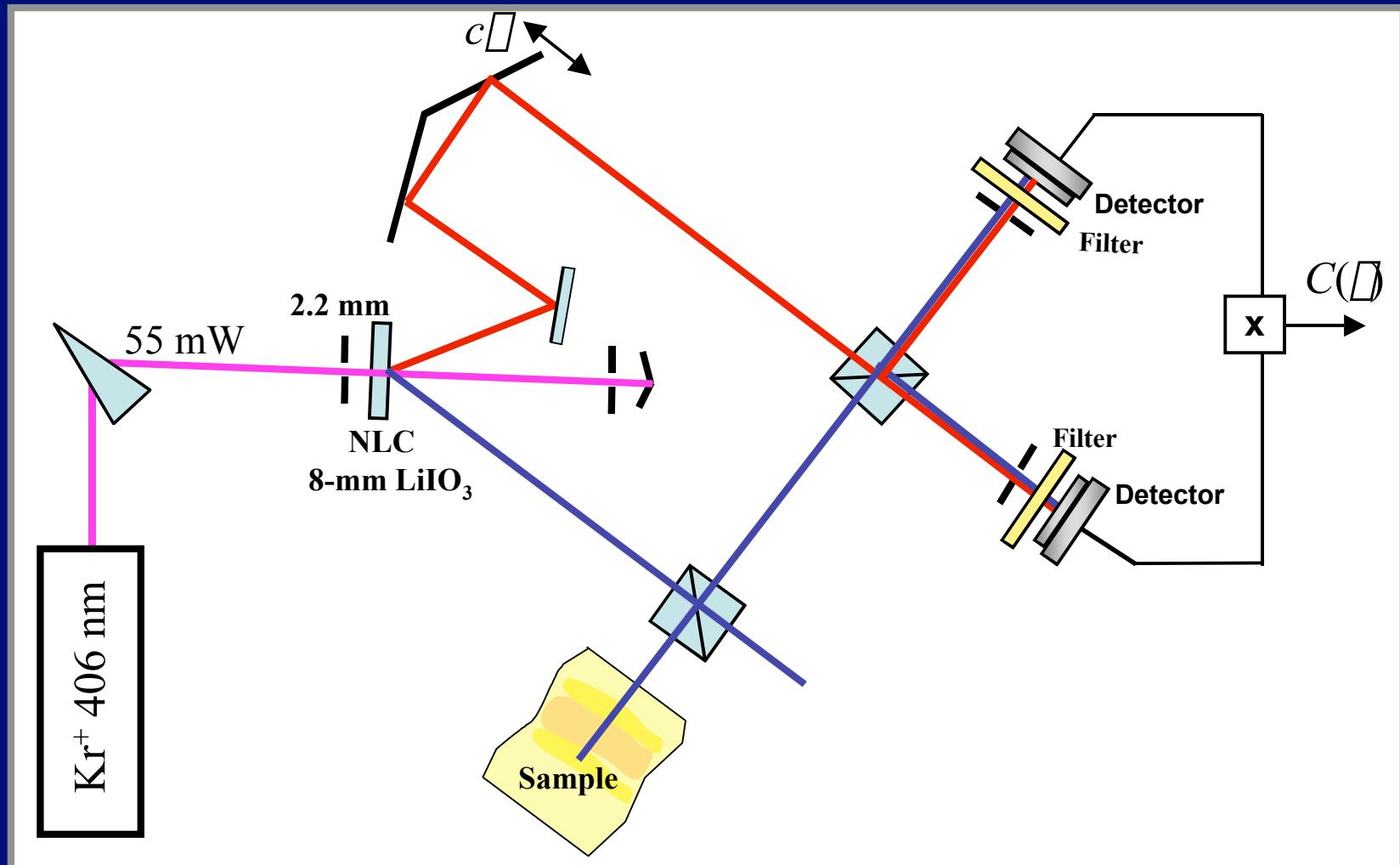
Q-OCT



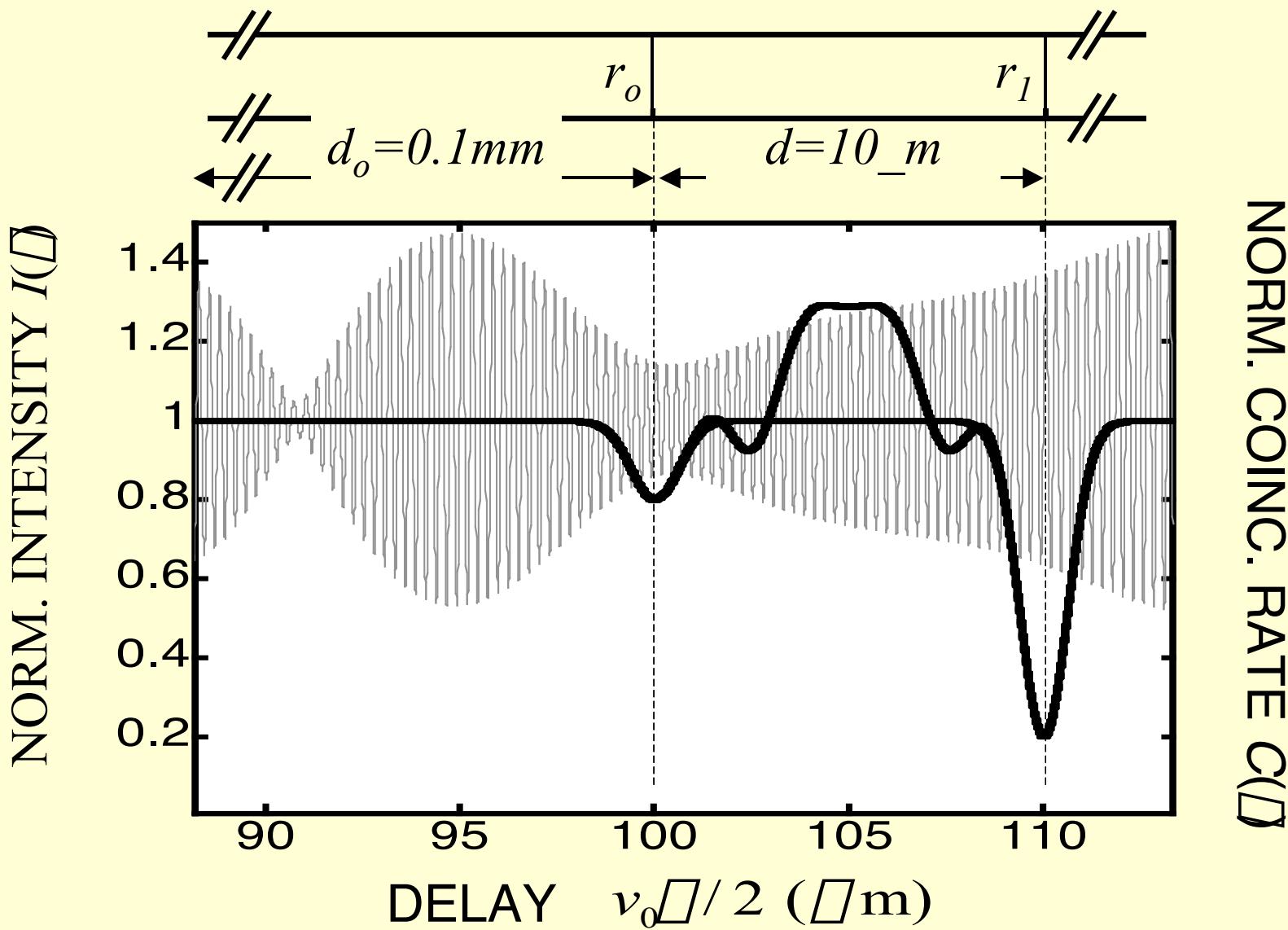
A. Abouraddy, M. B. Nasr, B. E. A. Saleh, A. V. Sergienko, and M. C. Teich

“Quantum optical coherence tomography with dispersion cancellation”, *Physical Review A*, v. 65, 053817 (2002).

Setup



A BURIED TWO-LAYER SAMPLE





SUMMARY



Quantum Physics
↓
Quantum Engineering
↓
Quantum Technology



Quantum Holography
Covert imaging and
Imaging
in hard to reach areas

Phase Imaging
Entanglement engineering
for quantum information
processing

Quantum Ellipsometry
Control of semiconductor and
polymer surfaces in research
and manufacturing

Quantum Tomography
Non-dispersive profiling
of semiconductor and
biological objects